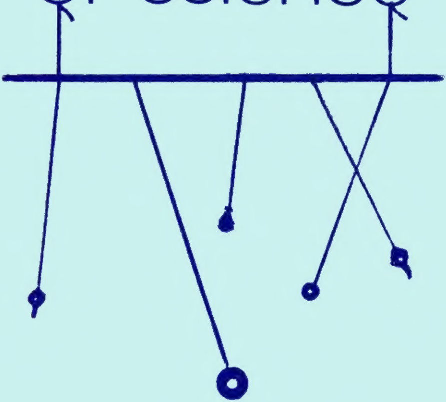
THINGS of science



PENDULUM

Created and distributed without profit by Science Service, Inc., 1719 N Street, N.W., Washington, D. C. 20036. E. G. Sherburne, Jr., Director. Ruby Yoshioka, Editor.

PENDULUM

The pendulum is a very ancient device that may have been used even before the discovery of fire by man. And today it still plays an important and diversified role in our daily lives, from its most simple form as playground equipment to complicated instruments in physical laboratories.

Man must have noticed very early in history that a weight hanging by a vine would swing back and forth above a central point when disturbed, thus leading to the invention of the first swing. A child swinging on a swing is making use of a pendulum, in fact he is an integral part of the pendulum.

A grandfather's clock ticking time away owes its steady rhythm to the swing of a pendulum. Galileo is said to have noticed the swinging of a large lamp in the cathedral at Pisa. He measured the time required for swings by counting his own pulse, the only means of measuring time that he had available. Since he was a medical student at the time, he thereafter used a pendulum for counting the pulse of patients. His discovery eventually led to his design for a pendulum clock.

What exactly is a pendulum and what are its characteristics? With the materials

in this unit, we will be able to observe some of the properties of the pendulum and their applications.

First look over your materials.

SCREW EYES—Two

LEAD SINKER—One.

WASHERS—Two; large and small.

WIRE—Eight inches long.

NAIL—One; $2\frac{1}{4}$ inches long.

PAPER CUP—Cone-shaped.

PAPER SCALE — For measuring the swings of a pendulum.

COLORED PAPER—One sheet; $8\frac{1}{2}$ x 11 inches.

PHYSICAL PENDULUM—Cardboard strip with $\frac{1}{8}$-inch diameter hole at one end; $1\frac{1}{4}$ x 11 inches long.

PENDULUM SUPPORT—To be constructed from die cut cardboard.

PLUMB LINE

Experiment 1. Take a piece of sewing thread about 15 inches long and attach it to the ring on the lead sinker. Allow the sinker to hang freely.

You have made a plumb line, an instrument familiar to all carpenters, engineers and builders since the time of the ancient Egyptians. The plumb line depends upon the force of gravity for its usefulness. Gravity pulls all objects toward the center

of the earth and a weight suspended from the end of a string, therefore, hangs straight up and down or vertically. Thus, this simple device can be used to check walls and other structures to be sure that they are perfectly vertical.

Experiment 2. Pull the sinker to one side and then release it so that it swings back and forth freely. The plumb line now is a simple pendulum.

A weight suspended from a fixed point that can swing freely back and forth in a circular arc about the fixed point is known as a simple pendulum.

We shall do various experiments with the simple pendulum, but first construct the support for your pendulums.

PENDULUM SUPPORT

To construct your pendulum support, follow the instructions given below:

(1) Separate the parts. You will have:

a. One crossbar (Fig. 1).

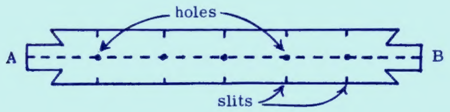


Fig. 1

b. Two posts (Fig. 2).

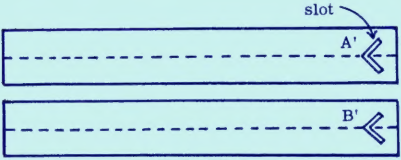


Fig. 2

c. Four braces—two 8 inches long; two 5½ inches long (Fig. 3) each with two 1/16-inch-wide slots.

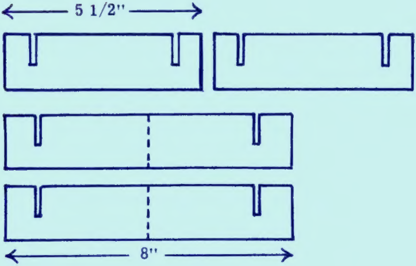


Fig. 3

d. One base (Fig. 4).

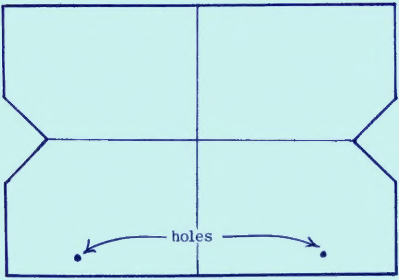


Fig. 4

(2) Fold the two posts lengthwise down the center along the scored line into right angles.

(3) Fold the two 8-inch braces crosswise at the center along the scored line into right angles.

(4) Glue the bottom of the posts—the unslotted end—to the inside of the angle of these braces tightly with the edges flush at the bottom. Allow the glue to dry completely (Fig. 5a).

Insert the slots of the 5½-inch braces into the slots of the 8-inch braces, pushing them in tightly so that the posts stand perfectly upright (Fig. 5b).

(5) Note the 5 small holes along the center of the crossbar. If necessary punch

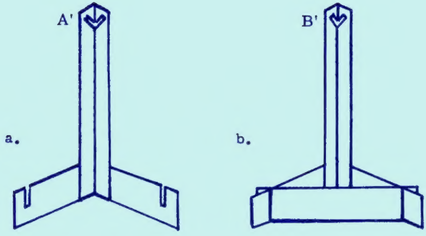


Fig. 5

out the holes carefully. Opposite each hole along the two edges, make slits about ⅛-inch long with a sharp knife or single-edge razor (Fig. 1).

Bend the crossbar lengthwise along its center along the scored line into a right angle. Number the holes 1 through 5 from left to right on the outside of the angle.

(6) Apply adhesive, such as epoxy glue, to the inside edges of the V-shaped slots A′ and B′ in the posts. Hold the crossbar so that the open end of the angle faces upward. Insert A and B of the crossbar into slots A′ and B′ from the outside of the angle (Fig 6). Allow the glue to dry, applying more if necessary to prevent any movement of the crossbar.

(7) Draw lines across the center of the

base from edge to edge. The lines should intersect at the center of the base (Fig. 4). Place the bottom of the posts into the triangular slots in the base and tape them so they will remain immovable (Fig. 6).

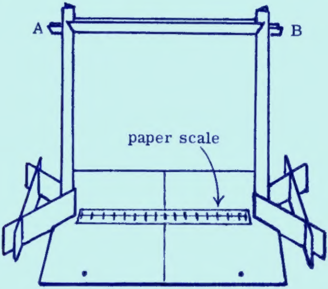


Fig. 6

(8) Paste the paper scale along the center line between the posts, matching the center of the base with the center of the scale (Fig. 6).

SIMPLE PENDULUM

Tie a 15-inch sewing thread to one of your screw eyes. Pass the free end of the thread through the center hole (#3) from the underside of the crossbar with the aid of a needle if necessary.

The weight on the end of the string or thread of a simple pendulum is called a bob.

Allow the bob to hang freely about ¼-inch above the base. Then insert the thread into one of the ⅛-inch slits you made. Now pass it through another slit on the opposite side of the bar. The slits will hold the thread firmly. It is not necessary to tie a knot. Leaving the end free in this way makes it easy to shorten or lengthen the thread, or to remove the pendulum without cutting the thread.

Be sure the pendulum hangs from the hole without obstruction. Keep this in mind in all your experiments.

Check to see that the screw eye points straight downward above the center of the scale below.

Experiment 3. Displace the pendulum toward one post and then release it. Observe that the bob swings along a circular path, along the arc of a circle whose center is the point of support of the pendulum.

When the pendulum reaches its highest point, it pauses briefly before descending. It increases its speed as it descends to its lowest point, and then slows as it rises again due to gravitational pull. The operator of a pendulum is gravity.

When the pendulum comes to rest, it is at a position of equilibrium. At the equilibrium position, the string hangs vertically and the center of gravity lies on a vertical

line below the support. In a simple pendulum the center of gravity is in the bob.

The center of gravity of an object is the point at which the whole weight of the object is considered to be concentrated. The center of gravity of a uniform regularly shaped object like the washer in your unit, is at its geometric center, or in the center of the hole. The center of gravity of the screw eye in your unit is along its axis about $\frac{1}{4}$ inch from the top; that of the sinker is about $\frac{1}{8}$ inch above the broad end and along its axis inside the sinker (Fig. 7).

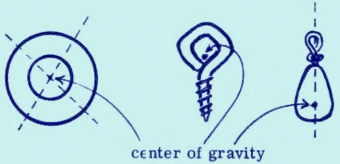


Fig. 7

The simple pendulum is an idealization in which the whole mass is considered to be concentrated at one point, the center of gravity of the bob, and the mass of the thread supporting it to be so small as to be negligible.

Experiment 4. Displace the pendulum to a point just above the 7 on the scale and allow it to swing back and forth. Does it

swing just above the 7 on the opposite side? A pendulum will swing an equal distance to the right and left of the equilibrium position.

The distance a pendulum bob travels from the point of equilibrium is called the amplitude of the swing.

Note that the amplitude of the swings gradually decreases until the pendulum finally comes to rest. This is due to the damping of the swings by friction of the air and at the point of support. If there were no friction to interfere with the motion, a pendulum would continue to swing with the same amplitude indefinitely.

PERIOD OF THE PENDULUM

Experiment 5. For this experiment you will need a watch or a clock with a second hand.

Displace the pendulum until it is over the 7 on the scale and then release it. Time the swings of the pendulum as it travels from one side of the scale to the other and back to the starting point. This is one full swing or one complete oscillation.

The time taken to complete one full swing or one complete oscillation is the period of the pendulum. The number of complete oscillations per second is the frequency of oscillation.

The period can be more accurately determined by observing the time required for ten complete oscillations and then dividing the time by ten.

Repeat the experiment several times and note down your results. Is the time always the same?

Repeat the experiment displacing the pendulum to the 3 on the scale, measuring the time for one complete oscillation as before. Are the periods the same for the swings of these tries as for those with larger amplitudes?

The period of a pendulum is the same for large and small amplitudes. This is true provided the arc of the swing is small (10° to 15°).

Experiment 6. Transfer the screw-eye pendulum to hole #2 making its length exactly 9 inches from the center of gravity of the bob to the point of support. Allow the pendulum to swing and note its period.

Now take your other screw eye and make a pendulum four inches long measured from the center of gravity to the point of support. When measuring the length of any of your pendulums, take the distance from the point of support to the center of gravity of the bob. Suspend this pendulum from hole #4.

Time the period for this pendulum.

Note your findings on a piece of paper. The period of the 9-inch pendulum should be 1½ times as long as that of the 4-inch pendulum.

The period of a pendulum is proportional to the square root of the pendulum's length.

The square root of 9 is 3 and the square root of 4 is 2. The ratio is 3 to 2. Three divided by 2 is 1½. Do your results show this?

Experiment 7. Now make one pendulum 8 inches long and the other 2 inches long. What is the difference in their periods? The period of the longer pendulum should be twice that of the shorter. Is it? Can you verify your result using the formula below for the period of a pendulum?

Galileo showed that the size of the swing has no influence on the time required for a swing of small amplitudes of the pendulum, but that it is the length of the pendulum that determines the period and that the time of a full swing varies as the square root of the length.

The mathematical formula for calculating the period of a pendulum is

$$T = 2\pi \sqrt{\frac{L}{g}}$$

where T is the period, L the length and g the acceleration due to gravity. π is equal to 3.14.

To calculate how long a pendulum must be for it to have a period of exactly one second we can solve for L using the above equation.

$g = 9.80$ meters/second^2 or 32.2 feet/second^2.

Squaring both sides of the above equation, you get

$$T^2 = \frac{4\pi^2 L}{g}$$

$$\text{then } L = \frac{gT^2}{4\pi^2}$$

If $g = 9.80$ m/sec^2 and $T = 1$ second,

$$\text{then } L = \frac{9.8 \text{ m/sec}^2 \times 1 \text{ sec}^2}{4(3.14)^2}$$

$$= 0.25 \text{ meters} = 25 \text{ centimeters}$$

If you use 32.2 ft/sec^2 for g, the answer will be expressed in feet. Multiply the answer by 12 to get the number of inches = 9¾ inches.

Experiment 8. Insert the nail horizontally into the edge of the base of your pendulum support near the center on the side opposite the two holes. Or you may tape the nail to the surface of the base at

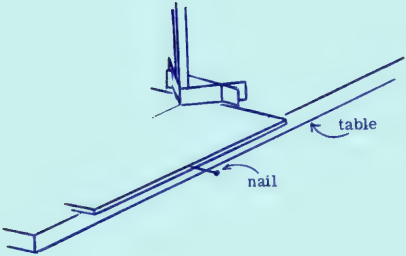


Fig. 8

this point. Allow the nail to protrude at least 1¼ inches and extend from the edge of a table (Fig. 8).

This will allow you to use a longer pendulum.

Weight the base down with a book or other object if necessary to prevent tipping.

Check the result you found in the above calculations by making a pendulum 9¾ inches long. Is the period one second?

How many inches long must a pendulum be to have a period of two seconds? How many centimeters? Refer to Experiment 7. Check your answer by both experimentation and calculation.

Experiment 9. Compute the period of a pendulum of any given length by the above equation and then check your answer by experimentation.

Use the pendulum support again for the following experiments through Experiment 14.

Experiment 10. Remove the screw-eye pendulums and replace them with the pendulums with the washers as bobs. Note the difference in weight of the two bobs. Make the two pendulums the same length.

Swing the two together in a small amplitude. Are their periods the same?

Note that the equation does not depend on the mass of the pendulum.

Galileo showed that the period of a pendulum is independent of its weight. This property is known as "isochronism."

The fact that the pendulum exhibits isochronism permits its use in clocks for regulating the timing mechanism. Also, the usefulness of the pendulum as a timekeeper is based on the fact that the period is not affected by its amplitude. Thus, if a clock runs down and the amplitude decreases slightly, the clock will still keep very nearly correct time.

Galileo, although he had become blind, dictated a description of a pendulum clock in 1641. A model of this clock was said to have been constructed by his student Viviani in 1649. This invention was not generally known and Christian Huygens, a Dutch scientist, some time later inde-

pendently invented a pendulum clock which became widely known. Both Galileo and Huygens have therefore been given credit for the invention of the pendulum clock.

Experiment 11. The period of a pendulum is influenced by the force of gravity as you can see from the equation given above.

The effect of gravity on the period of a pendulum can be demonstrated with a magnet to simulate the force of gravity. Using your screw-eye pendulum allow it to swing determining its period. (Be sure not to use the lead sinker pendulum. Why?) Now place a fairly strong magnet under the bob, just close enough so that the bob will be in its magnetic field. Does it swing faster? Now remove the magnet. Does the pendulum swing more slowly again?

The period of a pendulum is decreased if the force of gravity is increased.

Thus by knowing the length of a pendulum and the exact period, one can calculate the gravitational pull. The simple pendulum therefore is a convenient method of measuring gravity with great precision.

This principle is used widely in the field of geophysics in highly precise instruments

with a more complicated pendulum system. Local deposits of ores or oil can be determined by the gravitational force which is affected by the density of the earth's crust.

Would the time shown by a pendulum clock taken to the moon be slow or fast compared with earth time? The moon's gravitational pull is about 1/6 of that of the earth. Can you prove your assumption by the equation for the period of the pendulum?

$$g = \frac{4\pi^2 L}{T^2}$$

Experiment 12. Determine the period of any length of pendulum and solve the above equation for g to determine the value of g at your position on earth. Your measurements should be as precise as possible to obtain accurate results.

From the experiments you have performed, you have observed that the period of a pendulum is determined by its length and gravitational force, and that the weight of the bob and size of the amplitude have no effect on the period.

Experiment 13. As the pendulums are swinging, give one of them a slight sideways push so that it swings in an orbit. Does the period change?

The period of a pendulum is the same

for a given length whether it is swinging along a straight path or a circular one.

Experiment 14. Try this. Use a screw-eye pendulum and place the lead sinker on the base just below the equilibrium position of the pendulum so that the tip of the pendulum just touches the top of the sinker. Swing the pendulum in a circle and note that it circles around the object and does not strike it until it comes to rest.

Repeat the experiment letting the pendulum swing in an ellipse.

Experiment 15. Insert one of your screw eyes horizontally into the base of your pendulum support. Allow the screw eye to extend beyond the edge of the table as you did the nail.

Attach a thread about 36 inches long to your lead sinker and tie it to the screw eye. Allow the bob to hang an inch or so above the floor and then swing it in a wide amplitude. Note the height to which the bob rises.

As the pendulum is swinging hold a pencil about halfway down the length of the pendulum and directly under the support so that the pendulum strikes it.

What happens?

The bob rises to the same height as before, but faster and returns quickly.

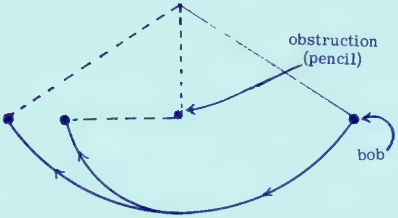


Fig. 9

But when the obstruction is removed, it resumes its former slower swing (Fig. 9).

The motion of the pendulum is like that of an object sliding down a surface without friction. The kinetic energy it gains in going down one side is just enough to carry it up an equal height on the other side. Therefore the pendulum rises to the same height.

Now lower the pencil to about 2 inches above the bob and release the pendulum from a large amplitude at a height above the obstacle (pencil). What happens?

The bob cannot rise to the same height as its starting point because the thread is too short so it will swing over and around the obstacle instead until it uses up its energy.

Experiment 16. The swing, as mentioned before, is a form of simple pendulum. What does a child do to swing

higher and higher without external help?

Using the lead sinker pendulum again, insert the 36-inch-long thread through the screw eye. Allow the bob to hang an inch or so above the floor as before. Then attach a toothpick or some other small object to the thread just above the screw eye to act as a stop so that the bob will not descend beyond the inch above the floor.

Now displace the pendulum slightly to produce a small swing. As the bob passes through the lowest point in its path, pull the thread a few inches and then lower it to the stop when it reaches the end of the swing. If you continue this repeatedly rhythmically with each swing, the pendulum will swing with a larger and larger amplitude.

This is essentially how a person works up in a swing—by shortening and lengthening the pendulum. As he rocks in the swing, he raises and lowers his center of gravity.

When you have achieved an amplitude large enough, shorten the thread quickly and the bob will make a complete circle over the point of suspension like the gymnastics of a circus performer.

What relationships do you see in this experiment with some of the other ex-

periments you performed?

COUPLED PENDULUMS

Experiment 17. Take your 8-inch wire and suspend it with sewing thread from holes #1 and #5 about ¾ inch below the bottom of the crossbar.

Hang any two pendulums about 7 inches long from the wire about three inches apart. Swing one of the pendulums and note what happens to the other. The energy of one pendulum is transferred to the other through the wire and back again causing them to swing alternately. Does one bob completely stop while the other takes up the swing?

Experiment 18. Repeat the experiment using one heavy pendulum and one light one. How does the difference in weight affect the swings? Try various combinations, with different lengths of pendulums.

Divert the swings so that one will move in a circle or ellipse and the other in a straight line. Observe the interchange between the pendulums. Swing them at right angles to each other. What happens?

Experiment 19. Now use all five pendulums, making them all the same length, about 7 inches long and placed an equal distance apart. Swing the one at the ex-

treme right. What happens? Try starting the swings with each of the others. Note the interesting sequence as each in turn begins to oscillate or takes a rest.

Experiment 20. Make a symmetrical arrangement of your pendulums with the two on the outside 7 inches long, the next two 3½ inches long and the center one 1¾ inches long. Swing one of the outside pendulums and note the sequence in which the other four pendulums begin to oscillate. Notice the differences in periods of the pendulums.

Note the effect the weight and length of one pendulum has on the other pendulums. What happens when you lower the wire and shorten the pendulums? When the suspending threads are at angles to the bar (Fig. 10)? Observe the pattern of

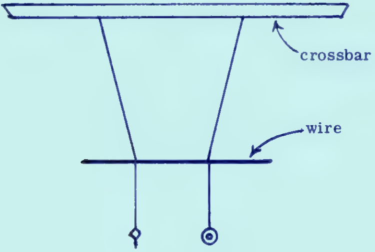


Fig. 10

oscillations.

There is an endless variety of experiments that you can do with coupled pendulums. Devise your own.

PHYSICAL PENDULUM

In the experiments with the simple pendulum, it was assumed that the weight of the pendulum was concentrated at one point and the mass of the thread was completely disregarded.

Experiment 21. Take the 1¼ x 11-inch strip of cardboard with the ⅛-inch hole and pass the nail through the hole. Insert the nail into the base of the support as before. Be sure the pendulum hangs freely without obstruction. The nail should extend at least 1¼ inches from the edge of the table.

A rigid pendulum such as this piece of swinging cardboard is called a compound or physical pendulum. The familiar clock pendulum is of this type. In a physical pendulum, the mass is distributed throughout the length, unlike the simple pendulum. All actual pendulums are physical pendulums.

Like the simple pendulums, when a physical pendulum is at rest, its center of gravity is along the vertical line below the point of suspension. The center of

gravity is located between the point of suspension and the tip of the pendulum. In a regular rectangular strip like the cardboard, it is at the center of the strip one-half the distance from the hole to the bottom of the pendulum.

Let us find the length of a simple pendulum that will oscillate with the same period as the physical pendulum.

Use the larger washer as the bob. Loop the thread over the nail in front of the physical pendulum without tying a knot so that you can lengthen and shorten the pendulum readily. Swing the two pendulums together in a small amplitude, pulling up or releasing the thread of the simple pendulum until the two pendulums oscillate together.

When the two pendulums swing together with exactly the same frequency, mark the length of the simple pendulum (the center of the hole of the washer) on the physical pendulum. Measure the distance from the point of suspension.

Is it about ⅔ the length of the strip?

This point is called the center of oscillation of the physical pendulum. Note that it is below the center of gravity.

The length of the equivalent simple pendulum will always be greater than the distance from the point of suspension to

the center of gravity of a physical pendulum.

SALT PENDULUM

Experiment 22. Cut a small hole about $\frac{1}{8}$ to 3/16 inches in diameter at the tip of your paper cup, just sufficient to allow a fine steady stream of table salt to pass through it. Do not make the hole too large.

Make two handles on the cup with threads inserted at right angles to each other about $\frac{1}{4}$-inch below the rim. Tie a heavy thread about 36 inches long at the point where the two threads intersect to make a pendulum with the cup (Fig. 11).

Fig. 11

Take your colored paper and draw a line one-half inch from the edge all the way around. Fold the edges inward along this line to make an upright border around

the paper. Fold the paper at the corners and tape them to make square rigid corners. The result is like a shallow box top. The rim around the paper will help prevent the salt from scattering.

Hang the paper cup pendulum from the nail in the base of the pendulum support so that it is about one inch above the floor. Place the colored paper just beneath it. Put about one tablespoon of salt into the cup, holding your fingers over the hole. Displace the pendulum, then release it, allowing it to swing within the margin of the paper. Note the pattern traced by the salt.

Repeat the experiment allowing the salt pendulum to swing in a circle or ellipse.

Experiment 23. A path traced out by a point which oscillates in simple harmonic motion (like a pendulum) simultaneously in two directions and at right angles to each other is called a Lissajous figure.

Using coupled pendulums we can produce patterns like Lissajous figures.

Make slits 1/16-inch deep along the edge opposite the two holes in the base of the pendulum support. Remove the 8-inch wire from the crossbar and suspend it from the two holes which are 7 inches apart. Allow it to hang about two inches below the base away from the edge of

the table. To secure the threads pass them through the holes several times and then pull the free end taut through the slits.

Suspend the paper cup near one end of the wire and about one inch above the colored paper. Near the other end of the wire, attach a simple pendulum with an object heavier than the cup containing salt as the bob.

Place about one tablespoon of salt in the cup and start it swinging. Immediately allow the other pendulums to oscillate in any direction. What kind of pattern does the salt pendulum trace?

Repeat the experiment swinging the pendulums in various directions and observe the various designs.

Lissajous figures are very useful for comparing the frequencies of oscillating instruments and for calibrating electrical oscillators. From the patterns obtained it can be determined whether the frequency is the same or different.

Experiment 24. Hang the salt pendulums from heavy thread shaped in a Y. To do this, tie a second thread to the cup. Loop a slip knot around the two threads and then suspend the free ends from the two holes in the base used for suspending the wire for the coupled pendulums.

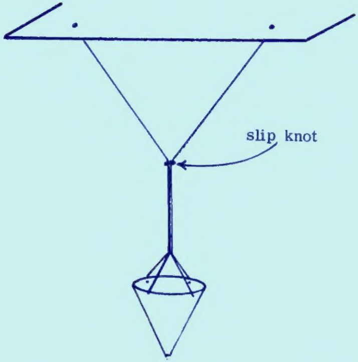


Fig. 12

Make the slip knot around the two threads just tight enough to hold the threads close together, but loose enough to slip up and down to shorten or lengthen the Y (Fig. 12).

Using one tablespoon of salt as before, swing the pendulum and note the interesting pattern produced. Repeat the experiment shortening and lengthening the Y to achieve different designs.

Larger figures can be obtained by using a longer pendulum and a larger sheet of paper for the tracings.

FOUCAULT PENDULUM

A pendulum can be used to prove the

earth rotates and also tell the time of day.

The French physicist, Foucault, showed that the pendulum is the simplest and most direct way to detect the earth's rotation. He suspended a pendulum about 220 feet along the dome of the Pantheon in Paris in 1852. As the pendulum swung, the line marked by the swinging weight rotated about the rest point of the pendulum. He calculated that if the pendulum is undisturbed by external forces, it would change in direction at the rate of 15° an hour. The pendulum was not actually rotating, but the rotation of the earth below was changing the position of the pendulum's direction of swing.

Experiment 25. To demonstrate the rotation of the earth below a freely swinging pendulum, suspend your sinker from a thread about 7 inches long from the center hole of the pendulum support. Allow the pendulum to swing at right angles to the support and as it is swinging rotate the support smoothly and steadily one complete turn (360°) being careful not to jar it. The base of the support represents the rotating earth.

Note that although the support is rotated, the pendulum continues to swing in its original direction.

You may wish to pivot the support with

a thumb tack inserted through the center of the base, securing it to a suitable surface, while still allowing it to rotate.

There are many applications of the pendulum in our daily lives and further investigation of the subject should be a most interesting project to pursue. For further reading, the references below will be helpful.

Elementary physics books.

The Attractive Universe: Gravity and the Shape of Space, E. G. Valens, The World Publishing Company, New York and Cleveland.

Physics Demonstration Experiments, Edited by Harry F. Meiners, The Ronald Press Company, New York.

Appreciation is expressed to Dr. Theodore Madey for reviewing this booklet.

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